Hot subdwarfs in the Galactic Bulge [1]

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ABSTRACT

Recent observations and theories suggest that extreme horizontal branch (EHB) stars and their progeny should be the cause of the UV excess seen in the spectra of many elliptical galaxies. Since the Galactic Bulge is the closest representation of an old, metal-rich spheroid in which we are able to study the EHB scenario in detail, we obtained spectra of bulge EHB star candidates and we confirm their status as hot evolved stars. It is the first time that such stars are unambiguously identified in the Galactic Bulge.

Subject headings: UV excess; Galactic Bulge; Extreme Horizontal Branch stars: general

1. Introduction

The spectra of elliptical galaxies and bulge regions of spiral galaxies in many cases show a strong and unexpected increase in flux at wavelengths shorter than 2500 Å. This "UV excess" was one of the most important discoveries of satellite based UV astronomy (Code & Welch 1969) but also a puzzle, since it requires the existence of hot stars in these old metal-rich systems. After a long debate most people agree that the observed UV radiation is mainly produced by very hot extreme horizontal branch stars (burning helium in

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their core) and their progeny, as Post-EarlyAGB and AGB-manqué stars (O'Connell 1999; Greggio & Renzini 1990, 1999; Dorman et al. 1995; Yi et al. 1998). This view is supported by spectroscopic (Ferguson et al. 1991; Brown et al. 1997, 2002) and photometric (Brown et al. 2002) UV observations of extragalactic systems. Near-UV HST observations of Brown et al. (2000) in M32 detected for the first time individual EHB star candidates in an elliptical galaxy. The best fit to these observations is achieved with evolutionary tracks for helium- and metal-rich populations, since in this case EHB stars have the longest lifetimes in the temperature range required to reproduce the UV excess.

The closest system similar to an elliptical galaxy with respect to age and metallicity, for which it is possible to resolve stars, is the Galactic Bulge. The vast majority of EHB stars known in the Milky Way, however, belongs to the metal-poor globular clusters (Moehler 2001) or to the disk population, where they show up as so-called subdwarf B [sdB] stars (Heber 1986; Saffer et al. 1994; Villeneuve et al. 1995; Altmann et al. 2004)

The first sdB candidates in the bulge were found in the two massive globular clusters NGC 6388 and NGC 6441 (Rich et al. 1997; Busso et al. 2004) which are, however, not typical for the bulge population. The situation changed recently: the imaging surveys of both Terndrup et al. (2004) and Zoccali et al. (2003) of bulge fields show a sequence of hot stars that are good candidates for EHB stars (see Fig. 1).

1.1. Disk Stars or Bulge Stars?

As the line-of-sight towards the Galactic bulge passes through the disk it is important to estimate the expected number of disk sdB stars in the observations. To do so we used the values of Villeneuve et al. (1995) for the space density of local field sdB stars ($2–4 \times 10^{-7}$ pc^{-3}) to derive the expected number of sdB stars along our line of sight from 4.5 kpc (corresponding to $I \approx 18.5$) to 11 kpc ($I \approx 20.5$) within the field of view of the Wide Field Imager (WFI, $30' \times 30'$). The sdB stars in the field of the Milky Way consist of a mixture of thin and thick disk stars (e.g. Altmann et al. 2004), so we assumed a ratio of 50:50. For the thin disk we used a scale height of 325 pc and a scale length of 3.5 kpc and for the thick disk we used values of 900 pc and 4.7 kpc, respectively (Larsen & Humphreys 2003). We used a distance to the Galactic center of 8.5 kpc and assumed that the disk ends at a radial distance of 1 kpc from the Galactic Center (Robin et al. 2003). This way we predict a total number of 4 to 9 sdB foreground stars within the full field of WFI. Using the values of Ojha (2001) for the scale lengths (2.8 kpc and 3.5 kpc) instead, we expect 7 to 14 foreground sdB stars. However, we detect many more bulge candidates (about 140) in the WFI photometry of Zoccali et al. (2003). Since they could be cool foreground stars with low reddening (instead

of reddened hot stars), we obtained spectroscopy of 29 candidates in order to derive effective temperatures and surface gravities and then, by means of comparison with HB models, to check their evolutionary status.

2. Observations and Data Reduction

Our spectroscopic targets were selected from the photometric catalogue of bulge stars obtained from Zoccali et al. 2003 (see Fig. 1). The field is located toward the Galactic center, at l=0°, b=−6°, where the average reddening is E_{B-V}=0.45 (Zoccali et al. 2003). We have chosen the stars with $18 < I < 21$ and $0 < V - I < 0.8$ and among them we selected the most isolated ones. After positioning as many slitlets as possible on EHB star candidates, the remaining ones were used to get spectra of cool main sequence and red giant stars that will be helpful for constructing the overall spectrum expected for these bulge regions.

We obtained medium-resolution spectra ($R \approx 1200$) of 29 EHB star candidates at the VLT-UT1 (Antu) with FORS2. We used the multi-object spectroscopy (MXU) mode of FORS2 with the standard collimator, a slit width of 0.7” and grism B600, which allows to obtain spectra in the range between 3650 and 5200 Å (not all candidates though have full spectral coverage because of the different positions on the CCD).

The data reduction was performed as described in Moehler et al. (2004) except for the following points. Due to the long exposure times (from 2700s to 5400s) the scientific observations contained a large number of cosmic rays and were therefore corrected with the algorithm described in Pych (2004). Regarding the subtraction of the sky background, we used two different methods depending on whether the target star in the slitlet was isolated or not. If the star was isolated, meaning any other stars in the slitlets were well enough separated from our target to identify regions uncontaminated by any stellar source, we approximated the spatial distribution of the sky background by a constant. If the slitlet showed severe crowding, meaning that the spectra of different stars were overlapping, we fitted each stellar profile with a Lorentzian function so that the whole spatial profile was reproduced by the sum of all the profiles; all profiles but that one of the target were then subtracted (for details see Moehler & Sweigart, 2006). With the extraction of the spectra, we saw that some (5 of 29) of our targets were actually cool stars. Therefore we did not proceed further with the reduction for these stars. The spectra were flux calibrated using standard star spectra and corrected for any Doppler shifts determined from Balmer lines, as in Moehler et al. (2004).

3. Analysis

Some examples of the spectra are shown in Fig. 2. The spectra of the hot stars show evidence for high reddening like a strong Ca II K line and the diffuse interstellar band at 4430 Å. To fit the spectra (except for one He-rich star) we used ATLAS9 model atmospheres for solar metallicity (Kurucz 1993) to account for effects of radiative levitation (see Moehler et al. 2000 for details), from which we calculated spectra with Lemke's version of the LINFOR program (developed originally by Holweger, Steffen, and Steenbock at Kiel University). The use of NLTE models or of LTE models with higher metallicity does not significantly change the results.

To establish the best fit, we used the routines developed by Bergeron et al. (1992) and Saffer et al. (1994), as modified by Napiwotzki et al. (1999), which employ a χ^2 test. The uncertainty necessary for the calculation of χ^2 is estimated from the noise in the continuum regions of the spectra. The fit program normalizes model spectra and observed spectra using the same points for the continuum definition. We used the Balmer lines H_β to H_{10} (excluding H_ϵ to avoid the Ca II H line), the He I lines at 4026, 4388, 4471, 4921 Å, and the He II lines at 4542 and 4686 Å.

We obtained the atmospheric parameters T_{eff}, log$g$ and helium abundances and we calculated the absolute V and I magnitudes expected for these values, assuming $M_{star} = 0.5 M_\odot$. We left out one star because the fit was unacceptably poor. Since the formal fit errors are underestimated by a factor 2–4 (Napiwotzki, priv. comm.) a formal error of 0.1 in log$g$ implies an error of 25%–50% in the distance. We therefore discuss the bulge membership only for those stars with a formal error in log$g$ of less than 0.1 because for the others (4 of 23) the uncertainty in the distance is too large. Then considering a distance from the Galactic Center of $\approx$ 8.5 kpc and a bulge radius of $\approx$ 1.5 kpc, we find that most of these objects are indeed bulge stars: of 19 hot stars with reasonable errors σ in the distance, 13 stars are in the bulge within 1 σ and 3 more are in the bulge within 3 σ. We thus found 3 probable disk EHB stars in our sample of 29 candidate EHB stars, which corresponds to a contamination of 10%.

The heliocentric radial velocities also suggest a bulge membership of most EHB stars. The field where we are looking is at Galactic coordinates l=0°, b=−6°, toward the Galactic center, i.e. the expected radial velocities for disk stars are around 0 km s^{-1}. Our velocities are distributed in a range between −200 and +300 km s^{-1}, in agreement with the values found for K giants in Baade's Window by Terndrup et al. (1995, between −240 and +194 km s^{-1}). We calculated a velocity dispersion of 110 ± 17 km s^{-1} from our bulge EHB stars: the expected value for the disk is 50–70 km s^{-1} (Lewis & Freedman 1989) while Terndrup et al. (1995) found for Baade's Window, at a distance of 8kpc, 80–110 km s^{-1}.

Finally we compare our results with horizontal branch theoretical tracks: in Fig. 3 we plot the values found for those stars which belong to the bulge in the (T_{eff}, $\log g$) diagram. The error bars are the formal errors from the fit procedure, but, as we already mentioned, these errors are underestimated and in addition, they do not include any systematic uncertainties, due to, e.g. sky subtraction, flux calibration, etc. The evolutionary tracks are from Yi et al. (1997) with metallicity Z=0.004 and helium abundance Y=0.2416. The Zero Age Horizontal Branch (ZAHB), where the star starts to burn helium in its core quietly, and the Terminal Age Horizontal Branch (TAHB), where the star has burned the 99% of the helium, are shown together with evolutionary tracks for stars with total masses of 0.49, 0.50, and 0.51 $M_{\odot}$ (respectively M_{env} = 0.0075, 0.0127, 0.0226 $M_{\odot}$). Our tracks end at 0.495 $M_{\odot}$, corresponding to M_{env} = 0.0075 $M_{\odot}$; since EHB stars may have $M_{env} < 0.005$ $M_{\odot}$, we extrapolated the ZAHB and TAHB to higher temperatures (dashed curves in Fig. 3) to guide the eye. Proper models for lower envelope masses will be calculated and used in a later paper. The observed points agree quite well with the theoretical tracks, therefore these objects are indeed EHB stars; some objects are above the TAHB meaning that they are in the post-HB phase and then evolving as AGB-manqué stars (Greggio & Renzini 1990).

Finally we want to mention that all stars except one (which is helium-rich) are helium deficient as expected from diffusion.

4. Conclusions

We observed spectra of 29 EHB star candidates in the Galactic Bulge, from which we estimated the atmospherical parameters T_{eff} and log$g$ to verify their evolutionary status. Five objects turned out to be cooler foreground stars with low reddening, and for another one the spectroscopic fit is unacceptably bad. Of the 19 hot stars with reasonable distance errors 16 lie within a radius of 1.5 kpc around the Galactic center at 8.5 kpc. Also the observed radial velocities support a membership of these stars to the bulge. This is the first time that of stars are observed in the bulge and our statistics show that either spectroscopy or multi-colour photometry is required to disentangle hot stars in the bulge from other sources. We will use these spectra and the parameters derived from them to construct the integrated spectrum of the galactic bulge from the UV to the optical, following the method of Santos et al. (1995). This study will verify the role, so far only predicted, of these stars regarding the UV excess in the elliptical galaxies.

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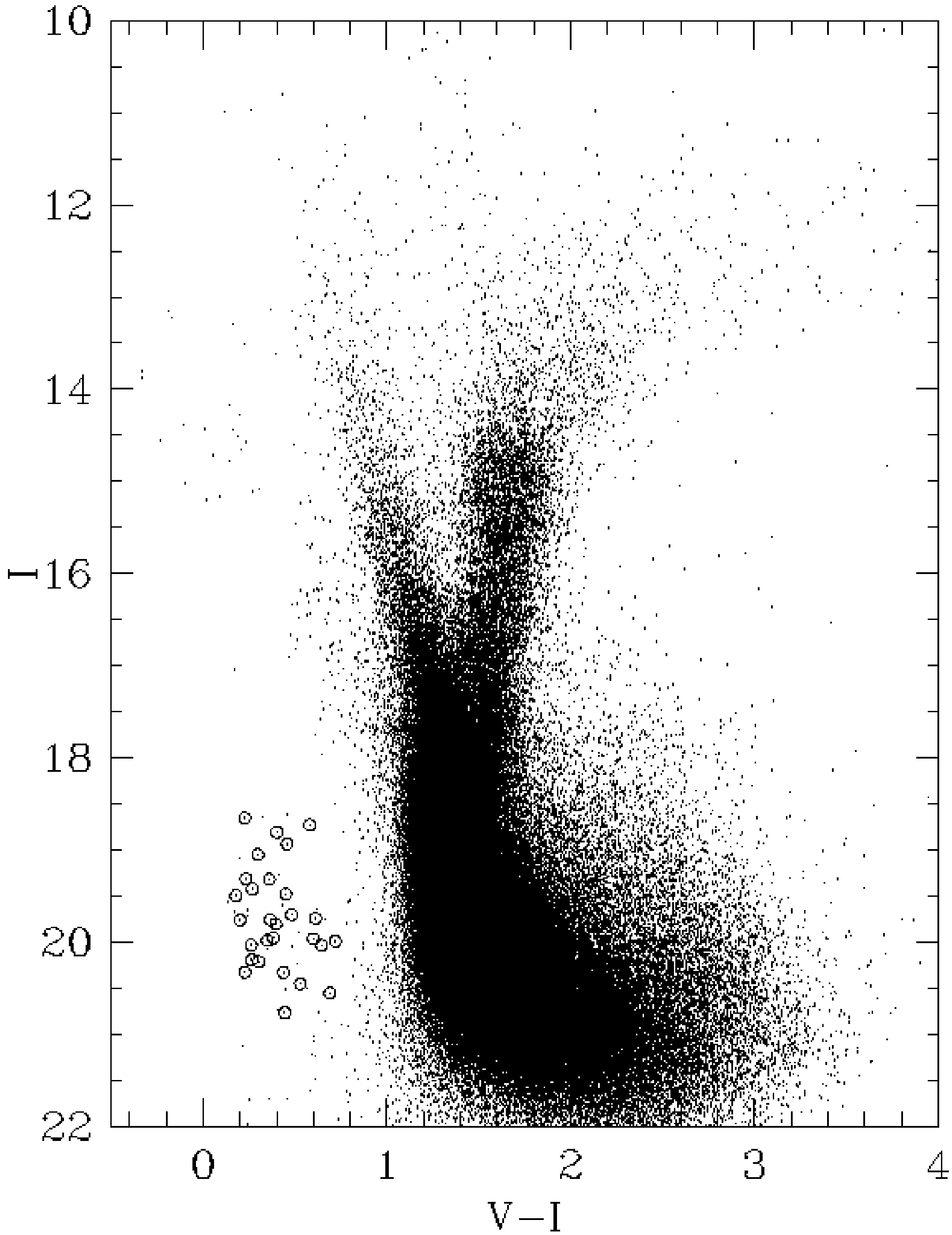
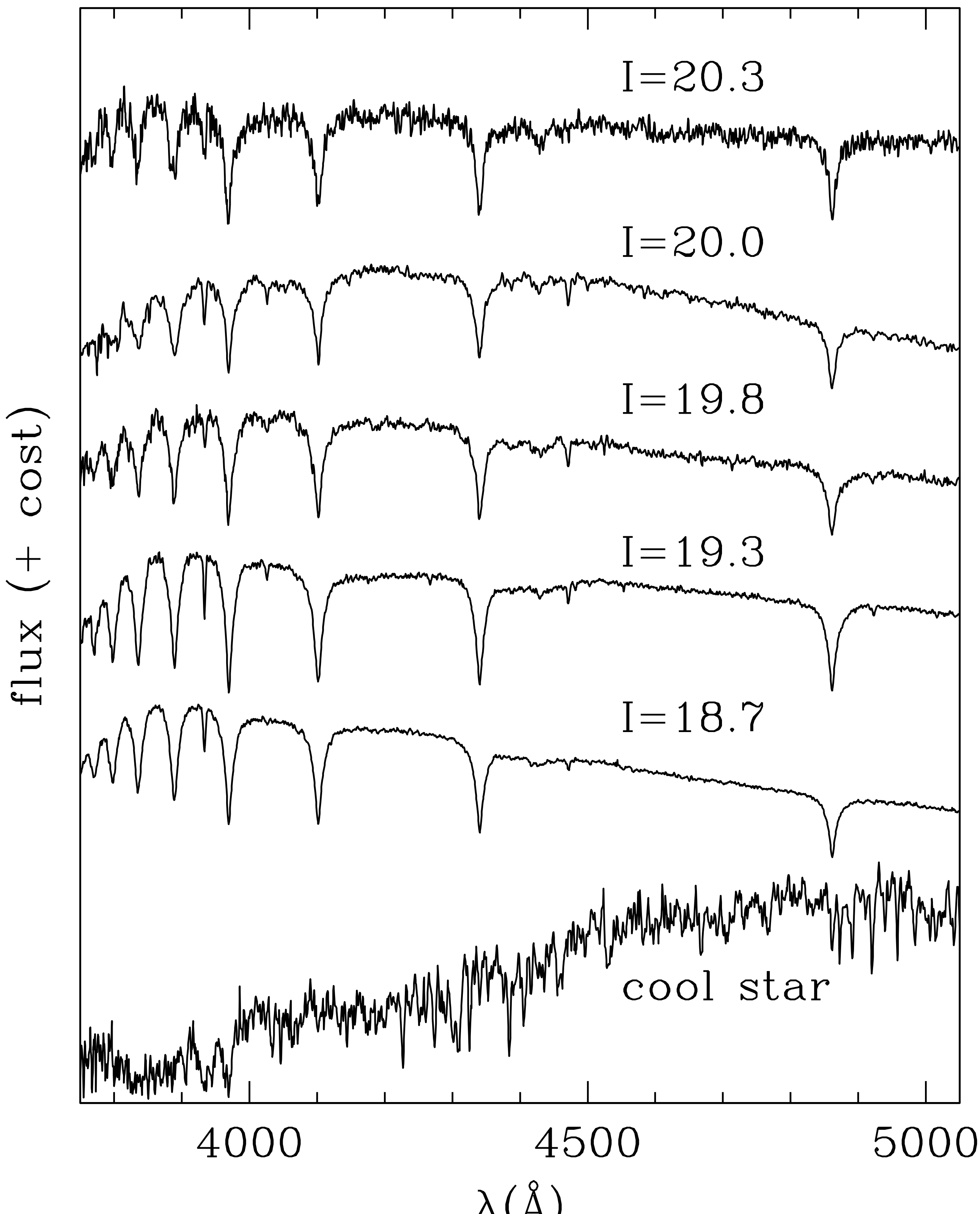


Fig. 1.— Colour-magnitude diagram of the Galactic bulge (at l=0°, b=−6°, E_{B-V}=0.45) obtained from the Zoccali et al. (2003) observations. Our targets are marked with circles.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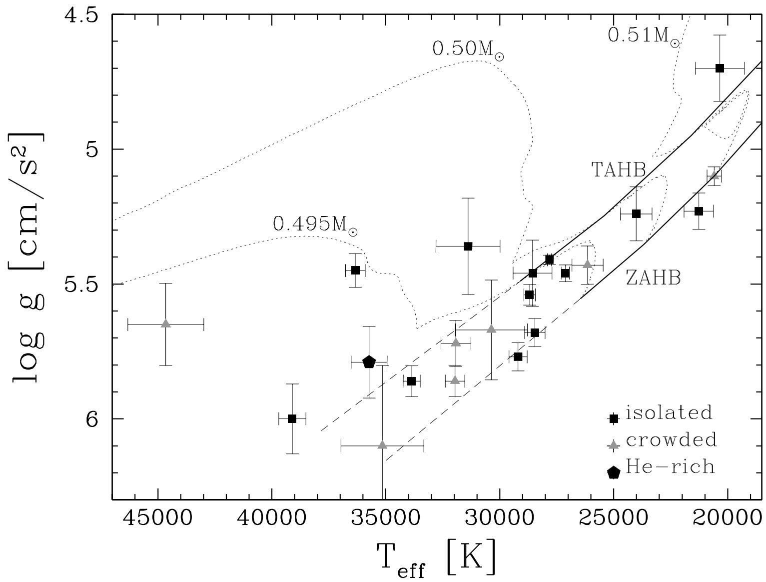

Fig. 3.— (T_{eff}, $\log g$) diagram: the squares indicate the isolated stars; the triangles indicate the crowded stars and the pentagon is the He-rich star. The ZAHB and TAHB (Yi et al. 1997) for Z=0.004 and Y=-0.2416 are plotted together with evolutionary tracks for 0.495, 0.50 and 0.51 $M_{\odot}$. The dashed lines are extrapolated from the ZAHB and TAHB tracks.